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Properties and Decays of the B_c^+ meson

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Recent studies of properties and decays of the B_c^+ meson by the LHC experiments are presented. Mass and lifetime measurements are discussed and some of the many new observed decays are reported.

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1 Introduction

The B_c^+ meson is the ground-state of a (\bar{b}, c) bound system. Being composed of two different heavy quarks it is a unique state in the Standard Model, offering an excellent laboratory to test both QCD and weak interaction. Indeed, being an open-favoured state, B_c^+ cannot decay through strong or electromagnetic interactions making weak interaction the only possible decay mechanism. Theoretical predictions indicate that 70% of the total decay width of the B_c^+ meson is due to c -quark decays, 20% to b -quark decays and 10% to weak annihilation [1]. Diagrams of the three categories are shown in Figure 1.

Experimentally, the B_c^+ was discovered at Tevatron in 1998 [2], where the CDF and D0 Collaborations observed three decays of the B_c^+ meson: the non-leptonic $B_c^+ \rightarrow J/\psi \pi^+$ decay and the semileptonic decays $B_c^+ \rightarrow J/\psi \mu^+ \nu$ and $B_c^+ \rightarrow J/\psi e^+ \nu$.

The LHC experiments contributed significantly to improve this picture by observing a number of new decays. Many of the observed decays have a J/ψ in the final state, plus several mesons, for example LHCb and CMS reported the observation of the decay $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ [3, 4]. LHCb also reported the observation of the decays $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$ and $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ [5, 6].

Other important observations reported by LHCb include the decay channels $B_c^+ \rightarrow \psi(2S) \pi^+$ [7], $B_c^+ \rightarrow J/\psi D_s^+$, and $B_c^+ \rightarrow J/\psi D_s^{*+}$ [8].

The decay $B_c^+ \rightarrow B_s^0 \pi^+$, observed by LHCb, represents the first observation of a B_c^+ decay due to a $c \rightarrow s$ transition [9], and is covered in Section 2. Production measurements are covered in Section 3, while mass and lifetime measurements are described in Sections 4 and 5, respectively.

2 Observation of $B_c^+ \rightarrow B_s^0 \pi^+$ decays

LHCb reported the observation of the $B_c^+ \rightarrow B_s^0 \pi^+$ decay analysing the pp -collision data collected in 2011 at a center-of-mass energy of 7 TeV, and in 2012 at a center-

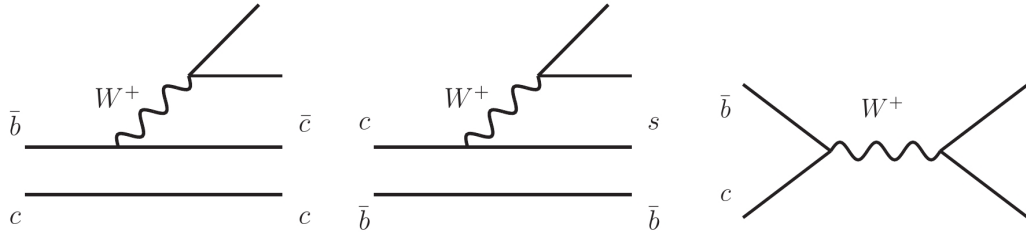


Figure 1: Feynman diagram of B_c^+ decays with the c -quark as spectator on the left, the b -quark spectator in the central figure, and through weak annihilation on the right.

of-mass energy of 8 TeV, corresponding to an integrated luminosity of 1 fb^{-1} and 2 fb^{-1} , respectively.

Predictions for the branching fraction $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$ span a large range between 2.5% and 16.4% (see Ref. [10], and references therein). LHCb has performed a search starting from two samples of fully reconstructed B_s^0 mesons decaying to $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow J/\psi \phi$. The distributions of the invariant mass of the B_s^0 candidates, as reconstructed in the two final states, are shown in Figure 2.

$73\,700 \pm 500$ $B_s^0 \rightarrow D_s^- \pi^+$ and $103\,760 \pm 380$ $B_s^0 \rightarrow J/\psi \phi$ candidates are observed and combined to a charged pion to create B_c^+ candidates. The distributions of the invariant mass of such candidates are shown in Figure 3.

The fitted signal yield for $B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+) \pi^+$ decays is 64 ± 10 corresponding to a statistical significance of 7.7σ ; for $B_c^+ \rightarrow B_s^0(\rightarrow J/\psi \phi) \pi^+$, 35 ± 8 signal candidates are observed, corresponding to a statistical significance of 6.1σ .

The B_s^0 and B_c^+ yields are corrected for the relative detection efficiencies, to obtain the efficiency-corrected ratios of $B_c^+ \rightarrow B_s^0 \pi^+$ over B_s^0 yields,

$$\left(2.54 \pm 0.40(\text{stat}) \pm 0.23(\text{syst})\right) \times 10^{-3}, \quad \text{and} \quad \left(2.20 \pm 0.49(\text{stat}) \pm 0.23(\text{syst})\right) \times 10^{-3}. \quad (1)$$

for B_s^0 reconstructed as $D_s^- \pi^+$ and $J/\psi \phi$ respectively. The systematic uncertainty is dominated by the uncertainty on the lifetime of the B_c^+ meson which results into an uncertainty on the selection efficiency of criteria based on B_c^+ flight distance. Such contribution is correlated between the two B_s^0 reconstruction channels, and is therefore taken into account separately when combining the results above to give the ratio of production rates multiplied with the branching fraction

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left(2.37 \pm 0.31(\text{stat}) \pm 0.11(\text{syst}) \pm 0.17(\tau_{B_c^+})\right). \quad (2)$$

Assuming a value for $\sigma(B_c^+)/\sigma(B_s^0)$ of 0.2 [9], one would obtain a branching ratio $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$ of about 10%, the highest branching fraction ever observed for a b -hadron weak decay.

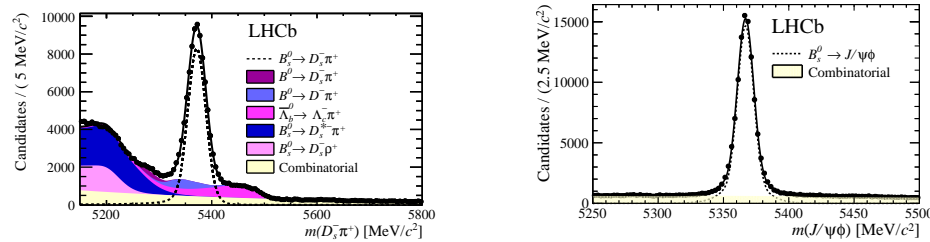


Figure 2: B_s^0 mass distribution for the candidates reconstructed as $B_s^0 \rightarrow D_s^- \pi^+$ (left) and $B_s^0 \rightarrow J/\psi \phi$ (right).

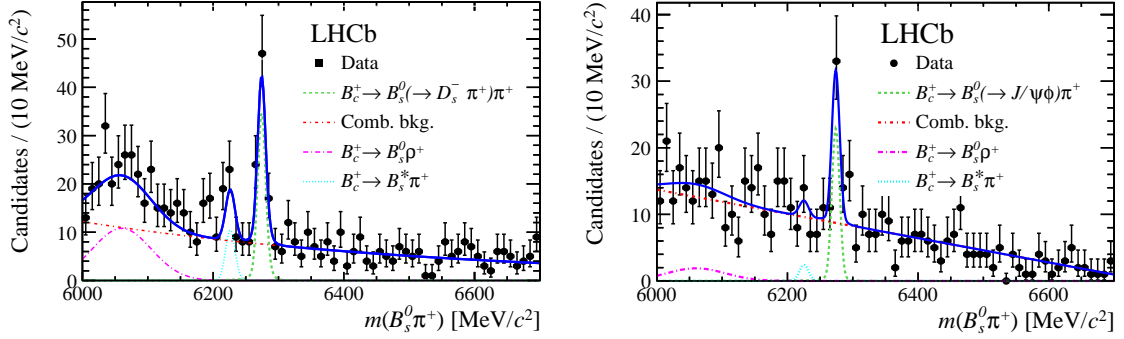


Figure 3: Invariant mass for the $B_c^0 \pi^+$ combinations with the B_s^0 reconstructed as $B_s^0 \rightarrow D_s^- \pi^+$ (left) and $B_s^0 \rightarrow J/\psi \phi$ (right).

3 Production measurements

The production mechanism of the B_c^+ meson at hadronic machines is expected to be quite different from the production mechanism of hadrons containing a single heavy quark. According to Ref. [11], the probability of a fragmentation of a b quark towards a B_c^+ state is about 11 order of magnitude lower than a fragmentation towards B^0 or B^+ states.

This means that other production mechanisms, mainly gg fusion processes, dominate the production of such states. Perturbative QCD calculations at the fourth order in α_s lead to expectations for the B_c^+ production cross-section at LHC between 0.4 and 0.9 μb , roughly corresponding to $10^{-3}\sigma(B_{u,d})$, ten times larger than the production cross-section at Tevatron [1].

Since no absolute branching fraction has never been measured for B_c^+ states, CMS and LHCb have used $B^+ \rightarrow J/\psi K^+$ as normalization channel, measuring the ratio

$$R_{c/u} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = \frac{N(B_c^+ \rightarrow J/\psi \pi^+)}{\epsilon_{tot}^c} \frac{\epsilon_{tot}^u}{N(B^+ \rightarrow J/\psi K^+)} \quad (3)$$

where $N(B_c^+ \rightarrow J/\psi \pi^+)$ and $N(B^+ \rightarrow J/\psi K^+)$ represents the number of reconstructed B_c^+ and B^+ decays, respectively, and are corrected for the total selection efficiencies ϵ_{tot}^c and ϵ_{tot}^u , respectively. The choice of the normalization channel $B^+ \rightarrow J/\psi K^+$ makes many of the uncertainties to cancel in the ratio.

Experimental values for $R_{c/u}$ were measured by CMS and LHCb in two different kinematical regions.

$$R_{c/u}^{\text{CMS}} = \left(0.48 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})_{-0.03}^{+0.05}(\tau_{B_c^+}) \right) \times 10^{-2} \quad (4)$$

with $p_T(B_c^+) > 15 \text{ GeV}/c$, $|y| < 1.6$, $\sqrt{s} = 7 \text{ TeV}$, $\mathcal{L} = 5.1 \text{ fb}^{-1}$ [3].

$$R_{c/u}^{\text{LHCb}} = (0.68 \pm 0.10(\text{stat}) \pm 0.03(\text{syst}) \pm 0.05(\tau_{B_c^+})) \times 10^{-2} \quad (5)$$

with $p_T(B_c^+) > 4 \text{ GeV}/c$, $2.5 < \eta < 1.6$, $\sqrt{s} = 7 \text{ TeV}$, $\mathcal{L} = 0.37 \text{ fb}^{-1}$ [12].

The third error is due to the uncertainty on the lifetime of the B_c^+ meson which reflects into an uncertainty on the selection efficiency of criteria correlated to the B_c^+ flight distance.

4 Mass measurements

The ATLAS and CMS Collaborations reported a preliminary measurement of the B_c^+ mass studying the decay channel $B_c^+ \rightarrow J/\psi \pi^+$. ATLAS performed the measurement using 82 ± 17 candidates, shown in Figure 4, left, collected in a dataset of pp collisions at $\sqrt{s} = 7 \text{ TeV}$ corresponding to an integrated luminosity of 4.3 fb^{-1} [13]

$$M(B_c^+)^{\text{ATLAS}(J/\psi\pi)} = 6282 \pm 7(\text{stat}) \text{ MeV}/c^2. \quad (6)$$

Analogously CMS performed a mass measurement on 330 ± 17 $B_c^+ \rightarrow J/\psi \pi^+$ candidates (see Figure 4, center) collected in a dataset corresponding to 4.7 fb^{-1} and found [3]

$$M(B_c^+)^{\text{CMS}(J/\psi\pi)} = 6272 \pm 3(\text{stat}) \text{ MeV}/c^2. \quad (7)$$

Using a small data sample collected in 2011 and corresponding to an integrated luminosity of 0.37 fb^{-1} , LHCb reported the world best measurement of the B_c^+ mass studying the channel $B_c^+ \rightarrow J/\psi \pi^+$ [14]:

$$M(B_c^+)^{\text{LHCb}(J/\psi\pi)} = (6273.7 \pm 1.3(\text{stat}) \pm 1.6(\text{syst})) \text{ MeV}/c^2 \quad (8)$$

The 162 ± 18 selected signal candidates were used to perform the mass measurement whose uncertainty was already dominated by systematic uncertainty on the momentum scale because of the large Q -value of the B_c^+ decay.

Better resolution and momentum scale calibration uncertainty have been obtained two years later studying the decay $B_c^+ \rightarrow J/\psi D_s^+$ [8]:

$$M(B_c^+)^{\text{LHCb}(J/\psi D_s^+)} = (6276.28 \pm 1.44(\text{stat}) \pm 0.36(\text{syst})) \text{ MeV}/c^2. \quad (9)$$

Up to date, this is the world's most precise single measurement of the B_c^+ mass.

The signal yield of 28.9 ± 5.6 $B_c^+ \rightarrow J/\psi D_s^+$ is small compared to the size of the sample available for $B_c^+ \rightarrow J/\psi \pi$, but because of the low Q -value of the decay, the experimental resolution, as shown in Figure 5, is much better and therefore the statistical uncertainties are similar for the two channels. The systematic uncertainty is still dominated by momentum scale calibration (accounting for $0.30 \text{ MeV}/c^2$) on the B_c^+ meson mass, while other relevant contributions are the uncertainty on the D_s^+

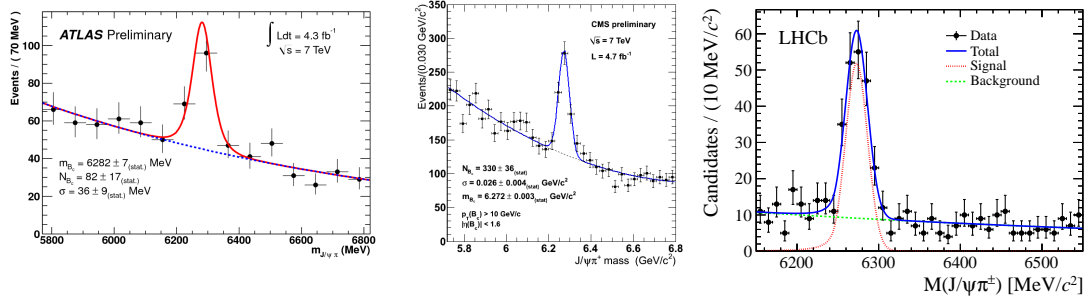


Figure 4: Invariant mass of the selected $J/\psi\pi^+$ combinations as used in the B_c^+ mass measurement by the ATLAS (left), CMS (center), and LHCb (right) Collaboration.

mass ($0.16 \text{ MeV}/c^2$), and signal modelling including simulation effects ($0.11 \text{ MeV}/c^2$). The uncertainty on the D_s^+ meson mass and on the momentum scale largely cancels in the mass difference

$$m_{B_c^+} - m_{D_s^+} = 4607.97 \pm 1.44(\text{stat}) \pm 0.20(\text{syst}) \text{ MeV}/c^2. \quad (10)$$

5 Lifetime measurement with the semileptonic decay channel $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$

The lifetime of the B_c^+ meson is an important quantity for both theory and experiments. Many models describing heavy-quark properties can be used to predict the B_c^+ lifetime, the more precise is the knowledge of this quantity, the more theoretical models are constrained.

Experimentally, the uncertainty on the lifetime results in an uncertainty on the selection efficiency of criteria based on the B_c^+ flight distance. Since these criteria are very powerful in rejecting background, most of B_c^+ analyses rely on them and are affected by lifetime uncertainty. In most of the analyses described above, the uncertainty on the world average for the B_c^+ lifetime is actually a dominant systematic uncertainty, so that a precise measurement of the B_c^+ lifetime will improve the precision on most of the results reported.

LHCb has recently measured [15] the lifetime of the B_c^+ meson by studying the semileptonic decay channel $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$, with the J/ψ reconstructed as a muon pair. The large branching fraction and the very clear experimental signature (a 3-muon vertex), allow this analysis to be performed with a cut-based decay-time-unbiased selection, avoiding the need to measure the acceptance as a function of the decay time, introducing the largest systematic uncertainty in most of the lifetime measurements.

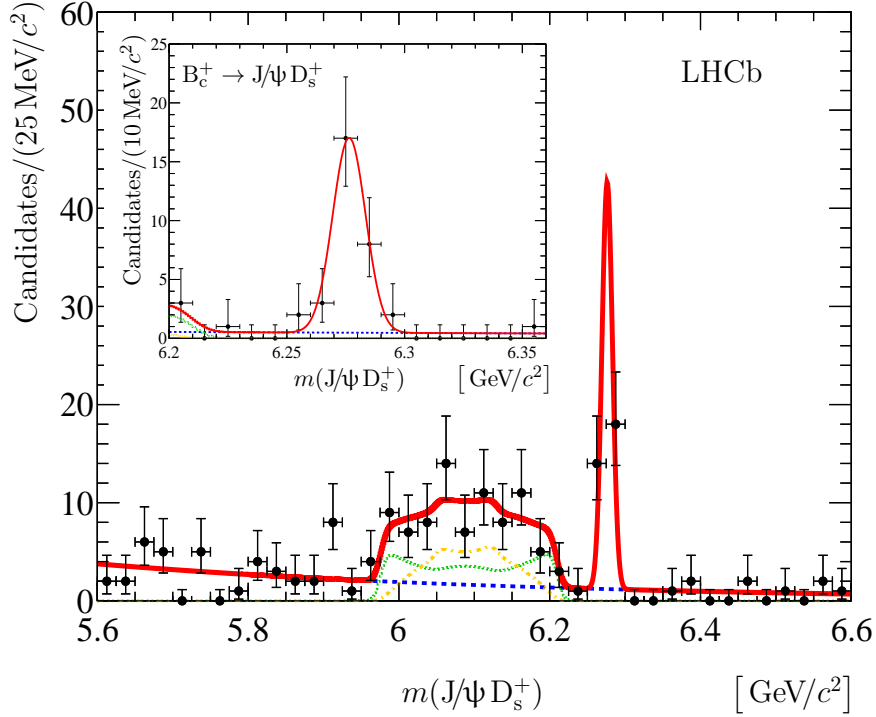


Figure 5: B_c^+ mass distribution for candidates reconstructed as $B_c^+ \rightarrow J/\psi D_s^+$ as used in the mass measurement. The broader structure at lower mass is due to partially reconstructed $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays.

On the other hand, when studying partially reconstructed decays background rejection is more difficult because the selection cannot rely on a mass peak. In the case of $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$, the invariant mass of the $J/\psi \mu^+$ combination lies in a range between 3.2 and 6.25 GeV/c^2 and the shape of the distribution depends on the form-factors of the decay, for which no experimental measurement is available.

A correction, named k -factor, between the $J/\psi \mu^+$ combination rest frame and the B_c^+ rest frame, needed to calculate the *proper* decay-time and therefore the lifetime. The k -factor correction is applied on a statistical basis in bins of the mass reconstructed for the $J/\psi \mu^+$ combination. The shape of the k -factor distribution is determined using simulation and is affected by: (i) form-factor model of the B_c^+ decay; (ii) model of acceptance and efficiency as function of the kinematic variables; (iii) feed-down decays, where the final state $J/\psi \mu^+$ is reached through an intermediate state, *e.g.* $B_c^+ \rightarrow \psi(2S)(\rightarrow J/\psi \pi^+ \pi^-) \mu^+ \nu_\mu$.

Background is dominated by events in which a real J/ψ from a b -hadron decay is associated to a hadron misidentified as a muon. This background source, named for brevity *misidentification background*, is modeled with a data-driven technique

requiring an accurate characterization of the PID performance of the LHCb detector.

Other non-negligible background sources are due to decay candidates with a fake J/ψ and candidates obtained combining a J/ψ with a muon, but not from the same vertex (combinatorial background).

The B_c^+ lifetime is obtained through a two-dimensional fit on the joint distribution of $M(J/\psi\mu^+)$ and t_{ps} , the decay time reconstructed in the $J/\psi\mu^+$ rest-frame.

The result,

$$\tau_{B_c^+} = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst) fs}, \quad (11)$$

is the world's best measurement of the B_c^+ lifetime, with an uncertainty halved with respect to the world average. The systematic error is dominated by the uncertainties on the background (± 10 fs), and signal (± 5 fs) models, where the latter includes theoretical uncertainties on form-factors and branching fractions of the feed-down decays.

Further improvements on the precision of the lifetime measurement are expected studying the hadronic decay channel $B_c^+ \rightarrow J/\psi\pi^+$ where systematic uncertainties are largely uncorrelated with those affecting the measurement presented above.

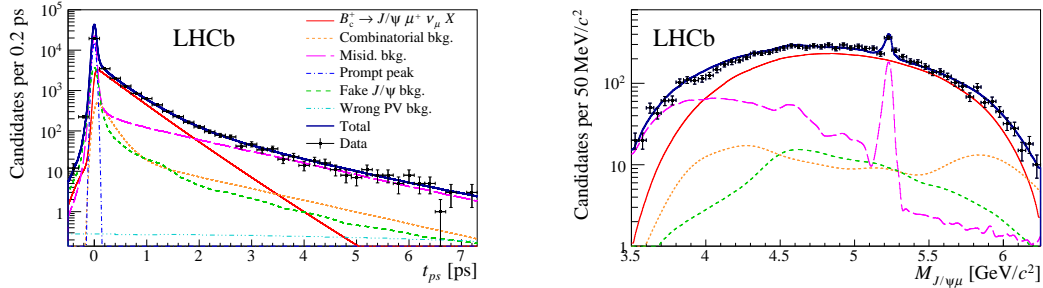


Figure 6: Data model for the $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$ decays used in the B_c^+ lifetime measurement. On the left the model is projected on the reconstructed pseudo-proper decay time, on the right on the invariant mass of the $J/\psi\mu^+$ combination.

6 Conclusion and outlook

The excellent performance of the LHC and of the detectors has allowed the LHC experiments to reach several achievements in the field of B_c^+ physics.

The world's best measurement of mass and lifetime were presented here together with the first observation of a $c \rightarrow s$ transition in a B_c^+ decay. Several other decay channels [4, 5, 6, 7, 16] have been observed for the first time and their relative decay branching fraction measured.

Between the FPCP meeting and the preparation of these proceedings new exciting results have been obtained. LHCb has published the measurement of the ratio of B_c^+

branching fraction to $J/\psi\pi^+$ and $J/\psi\mu^+$, using a data sample corresponding to an integrated luminosity of 1 fb^{-1} [17]. The ATLAS Collaboration has published the observation of an excited B_c^+ meson state decaying to $B_c^+\pi^+\pi^-$ [18].

In 2015, the LHC experiments will restart data-taking of the pp collisions at 13-14 TeV. Higher luminosity and larger B_c^+ production cross-section are expected and therefore many unobserved B_c^+ decay channels are expected to become accessible. Observed decays will be used as high-statistics control channels and studied for precision measurements.

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